The University of Chicago

GEOLOGY OF THE SHEEP MOUNTAIN REMNANT OF THE HEART MOUNTAIN THRUST SHEET, PARK COUNTY, WYOMING

A DISSERTATION SUBMITTED TO THE FACULTY
OF THE DIVISION OF THE PHYSICAL SCIENCES
IN CANDIDACY FOR THE DEGREE OF DOCTOR
OF PHILOSOPHY

DEPARTMENT OF GEOLOGY AND PALEONTOLOGY
1938

By
EDWARD H. STEVENS

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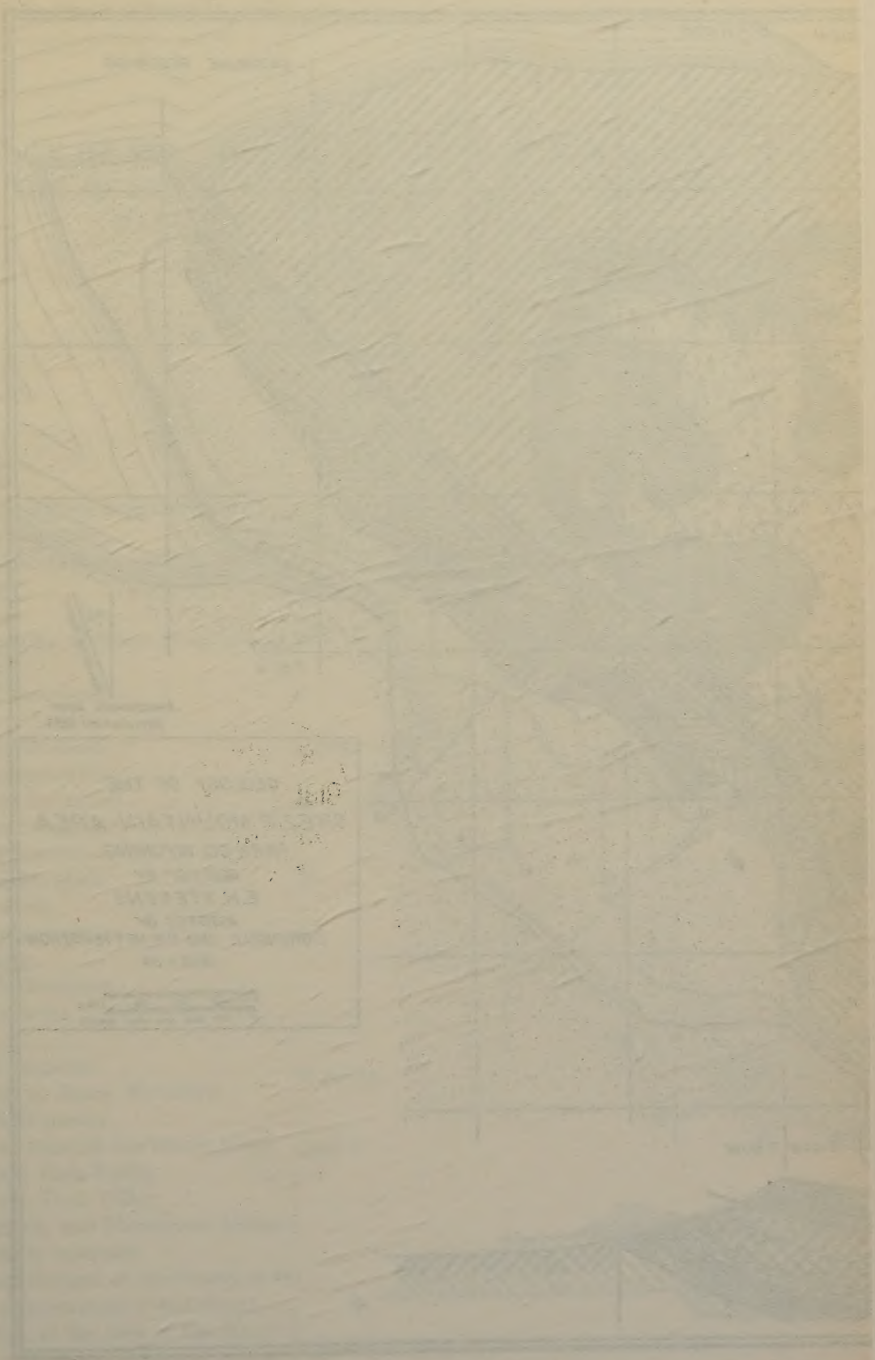

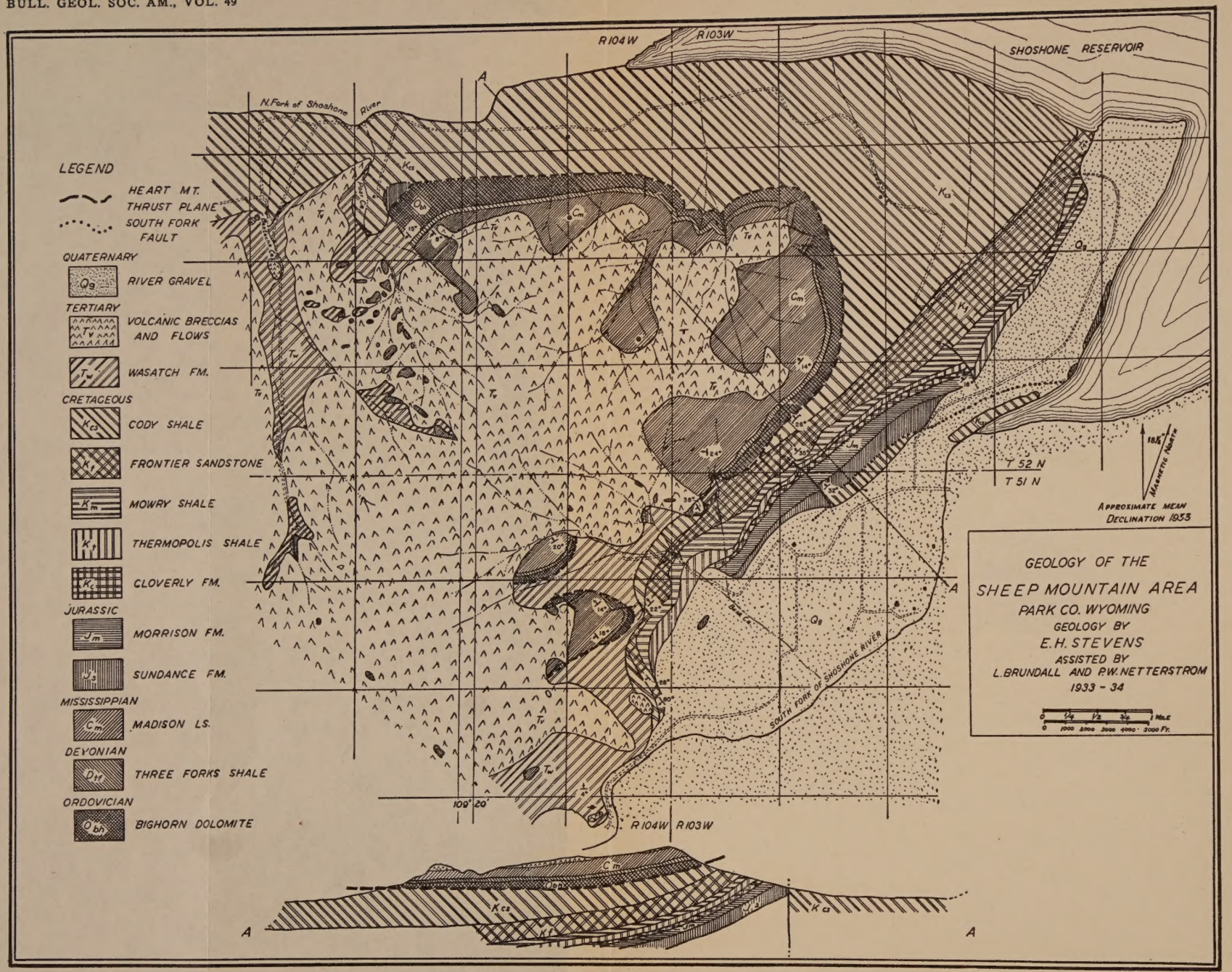

GEOLOGY OF THE SHEEP MOUNTAIN AREA

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GEOLOGY OF THE SHEEP MOUNTAIN REMNANT OF THE HEART MOUNTAIN THRUST SHEET, PARK COUNTY, WYOMING

BY E. H. STEVENS

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ABSTRACT

The present remnants of the Heart Mountain thrust sheet are in an area about 36 miles north and south and about 24 miles east and west. The town of Cody, Wyoming, is located at about the middle of the eastern edge of the area. The largest remnant of the thrust is Sheep Mountain, and, although a detailed study of this remnant failed to disclose proof of the mechanics of thrusting or of the direction of movement of the thrust mass, it did uncover evidence indicating that the movement of the mass was to the northeast and that two small remnants near Sheep Mountain were placed in their present position as individual blocks, separated from the main mass of Sheep Mountain. The position of some previously unknown remnants of the thrust is described. Mechanics of thrusting are suggested that will permit the independent emplacement of the two rotated blocks near Sheep Mountain and also explain the great extent of the fault in the direction of its movement. A history of the region is given in outline form to indicate the age of the various earth movements.

INTRODUCTION

LOCATION

The Sheep Mountain area is in Park County, Wyoming, about 30 miles east of the east entrance to Yellowstone Park and about 12 miles west of the town of Cody. The area mapped is triangular, about 6 miles on a side, bounded on the north by the north fork and on the southeast by the south fork of the Shoshone River. These branches are hereafter called respectively the North Fork and the South Fork. Between these forks lies Sheep Mountain, a large table-like remnant of the Heart Mountain thrust mass. The western limit of the map area is irregular, being determined by the western limit of large fragments of the Heart Mountain thrust sheet.

EARLIER GEOLOGICAL INVESTIGATIONS

The Heart Mountain "over-thrust" was first recognized and described as such by C. L. Dake (1918). At an earlier date the anomalous position of the Paleozoic limestone of Heart Mountain, apparently resting on the Wasatch sandstone, was recognized by C. A. Fisher (1906, p. 37), and the suggestion was made that these relations might be the result of a circular fault that punched the Paleozoic limestone up through the Wasatch formation.

Slightly later, Granger and Sinclair (1911), while working on the Tertiary deposits of the Bighorn Basin, noted Paleozoic limestones on the McCullock Peaks. They considered the possibility of overthrusting but concluded that perhaps the best explanation of the limestones' position was transportation by glacial ice.

In 1920, D. F. Hewett (1920) published a paper on the thrust, contributing much valuable information regarding its age and the extent of its plate.

Between 1920 and 1933 there were no contributions to the problem of the Heart Mountain thrust although the papers by both Dake and Hewett indicated that the nature of the thrust did not fit the characteristics of what might be called a "normal" overthrust. It was because of these features and because of certain similarities to the Ries Basin in Germany that W. H. Bucher (1933) suggested the possibility that the remnants of the Heart Mountain thrust were fragments left in their present position by the force of a large volcanic explosion.

The peculiar features noted by Bucher (1933, p. 238) are listed as follows:

> 1. Crustal deformation in the relatively simple, broad mountain-uplifts to the north, east, and south . . . has produced only local overthrusting to the extent of a very few miles at most. Overthrusting to a distance of 28 miles (minimum estimated by Hewett) would seem to require a mountain-uplift of correspondingly larger proportions. But the area west of the Heart Mountain overthrust-sheets and east of Yellowstone Lake is not wide enough to conceal . . . a mountain mass of dimensions much greater than those of the Beartooth Mountains.
> 2. The folds . . . beneath Heart Mountain as well as the two large asymmetrical folds of Rattlesnake and Pat O'Hara Mountains and the folds farther south along the western border of the Bighorn Basin are steepened on the western side; that is, they indicate movement from the east to the west. . . . The thrust masses on the other hand . . . moved from west to east. This is a most abnormal relation.
> 3. The west side of the overthrust limestone sheets abuts against and is overlapped by the thick volcanic agglomerates which form such conspicuous cliffs in the Shoshone Valley. Below these farther west lie bedded tuffs and later intrusive igneous masses. Nowhere is there any sign of the upthrust-center which must have acted as the plunger which is needed to push the limestone-sheets far out to the east.

Other peculiar features of the thrust that were not noted in Bucher's paper are as follows:

4. The exposed thrust remnants are composed only of the Bighorn, the Three Forks, and the Madison formations. As the total thickness is only about 1500 feet, it seems strange that these alone should make up a thrust mass having such great displacement.

5. The area of the thrust remnants has about the same length normal to the direction of movement as parallel to it. Is this the original size of the thrust sheet or is it only what remains from the erosion of a more extensive thrust mass?

6. Between the easternmost remnants of the thrust sheet and those farther west rises the long ridge of Rattlesnake Mountain. Did the

material of the thrust travel over this ridge, as suggested by Hewett (1920, p. 554), or has there been a major elevation of Rattlesnake Mountain since the thrusting?

PURPOSE OF SURVEY

The writer became interested in the problem of the Heart Mountain thrust, through R. T. Chamberlin, who with W. T. Thom, Jr., and W. H. Bucher, was in charge of the structural investigations undertaken by the Yellowstone-Beartooth-Bighorn project. Through detailed mapping of the Sheep Mountain remnant of the thrust mass, it was hoped that information could be obtained that would indicate whether the mechanics of thrusting were of the conventional type, or whether there was evidence confirming the explosion theory suggested by Bucher. In addition to the mapping of Sheep Mountain, the writer planned to explore some of the surrounding unmapped areas, to determine if other thrust remnants would indicate more accurately the limits of the thrust plate.

FIELD WORK AND ACKNOWLEDGMENTS

The field work on which this report is based was done during the summers of 1933 and 1934, under the auspices of the Yellowstone-Beartooth-Bighorn Research Association and under the direct supervision of R. T. Chamberlin and W. H. Bucher. The work was made possible by grants from the Geological Society of America, which the writer gratefully acknowledges. During the first summer's field work the writer was ably assisted by Laurence Brundall and the following summer by Paul Netterstrom.

The writer also wishes to express his great indebtedness to Professor Chamberlin and Professor Bucher for their many valuable suggestions both in the field and in the preparation of the manuscript. During the field work the writer had many illuminating discussions with the late Professor C. L. Dake, with Professor W. T. Thom, Jr., and with many other men working in the neighborhood of Sheep Mountain. It is impossible to mention by name all those whose co-operation has been of assistance to the writer. Such a list would include the many people associated with the Yellowstone-Beartooth-Bighorn project and a good part of the population of Cody, Wyoming.

PHYSIOGRAPHY

REGIONAL

The Sheep Mountain area lies on the east side of the Absaroka Mountains where the thick cover of Tertiary volcanics gives way to the sediments of the foot-hills on the west side of the Bighorn Basin. The maximum regional relief is about 6500 feet. Trout Peak, about 12 miles

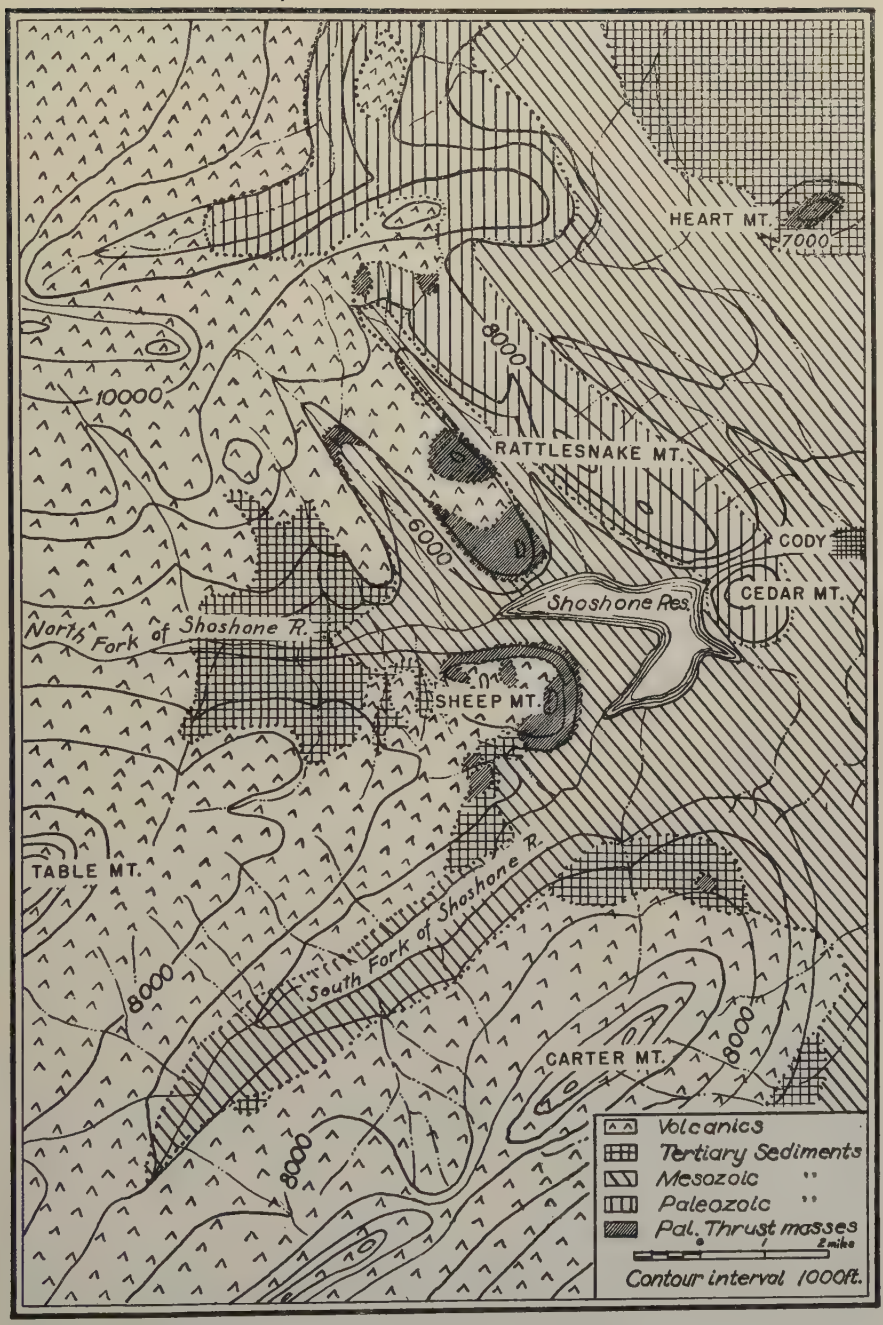


FIGURE 1.—*Topography and general geology of the area west of Cody*

northwest of the area mapped, has an altitude of 12,259 feet, whereas that of the Shoshone Reservoir, bounding the east side of the Sheep Mountain area, is about 5380 feet. Figure 1 is a topographic sketch map of the region, giving the general setting of Sheep Mountain. The contour interval is 1000 feet. Larger features of the geology are shown by line patterns.

The dam that holds back the waters of the Shoshone Reservoir is built in the narrow part of the Shoshone Canyon, a gorge, 1500 feet deep, cut through the southern tip of Rattlesnake Mountain, just below the junction of the North and the South forks of the Shoshone River.

Rattlesnake Mountain is a long ridge, extending from northwest to southeast, with its crest at an altitude of about 9000 feet. It has been mapped both topographically and geologically by G. D. Johnson (1934). The southern tip of the mountain, cut off from the rest of the ridge by the Shoshone Canyon, is called Cedar Mountain.

South of Cedar Mountain, and between it and Carter Mountain, there is a wide low col whose floor is at an altitude of about 5700 feet, only a few hundred feet above the river in the Shoshone Canyon. There is no stream flowing through the col at the present time and no conclusive evidence that any major stream has ever flowed through it. Its low elevation seems to be the result of rather rapid slope wash and deflation in the soft shale between the mountains. One of the problems of the region is to determine why the Shoshone River cut a canyon through the hard rocks of the Rattlesnake uplift rather than through the soft rocks 3 miles to the south.

In general, the Absaroka Range, lying north, west, and south of Sheep Mountain, is a series of long, flat-topped volcanic ridges extending between the major valleys. The altitude of the top of the ridges is about 11,000 feet, whereas that of the bottoms of the larger valleys ranges from 5500 to 8000 feet. Where the streams have cut through the thick succession of volcanic rocks into the underlying sedimentary rocks, the valleys are box shaped, with very steep walls in the volcanics and rather flat floors developed in the sediments. Where the streams are entirely in the volcanics the valleys are mostly V-shaped, although U-shaped valleys due to glaciation are present. An excellent description and interpretation of the topography near the head of the South Fork Valley has been published by J. T. Rouse (1934).

PHYSIOGRAPHY OF SHEEP MOUNTAIN

Sheep Mountain itself is a plateau, bounded on the north, the east, and the southeast by nearly vertical cliffs. The southeastern rim is the highest, rising to an altitude of 7800 feet. The northern edge of the

plateau is practically level, with an average altitude of 6800 feet. Plate 2, figure 1, is a view of the north-facing cliffs of Sheep Mountain.

At the foot of these bordering cliffs, there is a narrow shelf, from 50 to 300 feet wide, which drops away on the outer side into a steep-slumped

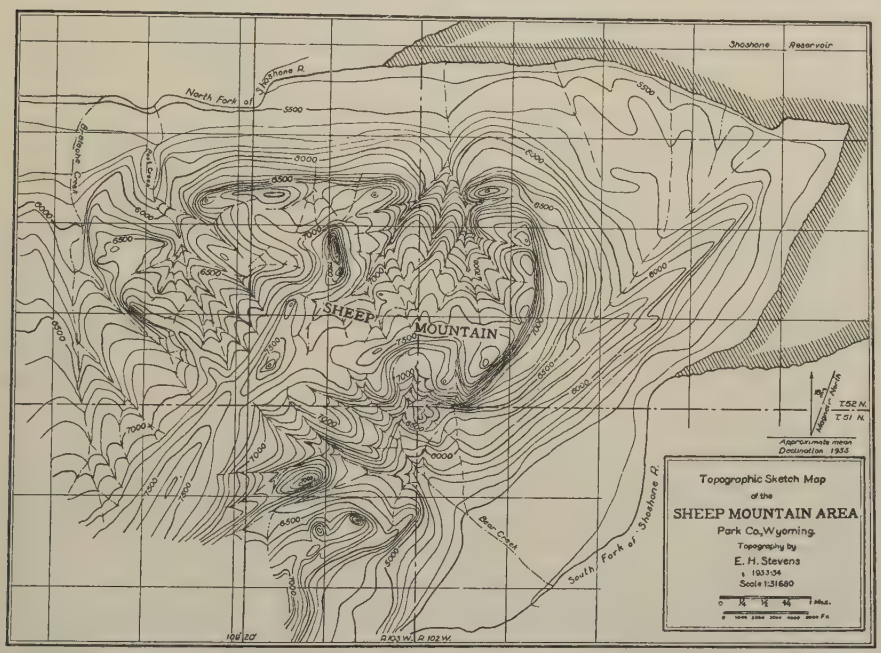


FIGURE 2.—*Topography of the Sheep Mountain area*

slope of Cretaceous shale. This slope descends to the rather flat area that is immediately adjacent to the rivers. Aligned with the southeastern face of the plateau and extending beyond it to the northeast, there is a low hogback ridge formed by the resistant beds of the Frontier formation. This ridge parallels the South Fork Valley.

The western edge of the Sheep Mountain plateau is not well defined, as it is overlapped by the eastern edge of the Absaroka volcanic accumulations that make up the mountains to the west. A partial division between the plateau and the volcanics has been made by two streams that have cut in at the western edge of the plateau. These streams are Post Creek, tributary to the North Fork, and Bear Creek, tributary to the South Fork. They have established a col between Sheep Mountain and the volcanic highland to the west, known as Table Mountain.

The top of Sheep Mountain, as can be seen from the elevation of the rim, slopes to the north at an angle of about six degrees. It is open rolling country with a relief of about 300 feet. The valleys are close together so that a section perpendicular to the drainage would show a series of rounded valleys and ridges, the valleys having a greater radius of curvature than the ridges. Plate 2, figure 2, illustrates this topography. The valleys over most of the plateau trend northward, merging and becoming more canyon-like until, at the north rim of the plateau, they are in three deep canyons that lie within three quarters of a mile of each other (Pl. 2, fig. 3). Within a mile from the edge of the plateau, the streams from these canyons join to form a single stream. Because of the arid climate the valleys on the plateau carry water only while the snow is melting or after a very heavy rain. There are two intermittent springs on top of the plateau at the contact between the limestone and the overlying volcanics, but the water from them evaporates after flowing only a short distance.

STRATIGRAPHY

GENERAL STATEMENT

Because there are only slight differences between the Sheep Mountain section and the better-exposed Rattlesnake Mountain section, only a brief description of the formations will be given in this paper. For more complete stratigraphic descriptions the reader is referred to papers by Johnson (1934), Hewett (1912), Tomlinson (1917), Darton (1906a, 1906b), Blackwelder (1918), and Lovering (1929).

A comparison between the section in the Sheep Mountain area and that exposed on Rattlesnake Mountain is made in Table 1. The thicknesses in the Rattlesnake Mountain section are taken from Johnson's paper (1934). Those in the Sheep Mountain section were measured by the writer, but, because of obscured contacts due to slumping, some of them are probably not accurate. Measurements of the Mesozoic formations were made on one flank of the South Fork anticline, where thinning during folding has probably reduced the thickness of the soft formations.

BIGHORN DOLOMITE

The oldest formation in the Sheep Mountain area is the Ordovician Bighorn dolomite. Throughout most of the formation the bedding is massive and the dolomite has a buff color, but in the upper half of the formation there occur two rather thin beds of a white chalky dolomite. These beds are persistent and are useful as horizon markers. Within the map area the Bighorn formation is found only in the thrust sheet. It rests on the Cretaceous Cody shale and the Eocene Wasatch formation, and is overlain by the Devonian Three Forks shale.

TABLE 1.—*Comparative thickness of formations in the Rattlesnake and Sheep Mountain regions*

TIME	RATTLESNAKE MOUNTAIN SECTION	Feet	SHEEP MOUNTAIN SECTION		Feet
Miocene	Breccia		Breccia		
Eocene	Wasatch (east of Cody)	1000	Wasatch	0–?	(900)
	Ft. Union	5600			
	(unconformity)		(unconformity)		
Cretaceous	Lance	1800			
	Meeteetsee	900			
	Mesaverde	1200			
	Cody	1800	Cody	0–?	(800)
	Frontier	495	Frontier	500	
	Mowry	375	Mowry	——	
	Thermopolis	650	Thermopolis	600	
	Cloverly (Greybull member)	110	Cloverly (Greybull member)	280	
Jurassic	Morrison	620	Morrison	300	
	Sundance	493	Sundance	(base not exposed)	
Triassic	Chugwater	800	.....		
Permian	Embar	210	*		
Pennsylvanian	Tensleep	180			
	Amsden	172			
Mississippian	Madison	900	Madison	(top eroded away) Max. 800	
Devonian	Jefferson	180			
	Three Forks		Three Forks	200	
Ordovician	Bighorn	450	Bighorn	(base not exposed) about 400	
Cambrian	Gallatin	512	.....		
	Gros Ventre	573			
	Flathead	145			
Pre-Cambrian	Granite	?			

* In the Sheep Mountain section the portion between the dotted lines is in the thrust sheet and rests on the Frontier, the Cody, and the Wasatch formations.

THREE FORKS SHALE

It is in the character of the Devonian formation that there is the greatest difference between the Rattlesnake section and the Sheep Mountain section. The Devonian of Rattlesnake Mountain, as described by Johnson (1934), consists of a group of soft orange-buff limestones and yellow-green shales which he correlates in part with the Three Forks and in part with the Jefferson formation. In the Sheep Mountain region the Devonian exposed in the thrust block consists of several beds of a buff lime breccia that weathers on the surface in a network of fine lines. In general, these beds underlie a bed of black and purple shale, but the contact between the two types of rock is not sharp, there being an interbedding of the lime breccia and the purple shale. The thickest of the beds of the lime breccia commonly stands out as a cliff about 20 feet high. No fossils were found in either type of rock.

The Devonian formation of Sheep Mountain is tentatively correlated with the Three Forks formation, on the basis of a lithologic similarity with the section described by Lovering in the Cooke City region, about

50 miles northwest. His description of the Three Forks formation is as follows (Lovering, 1929, p. 28):

"About ten feet of purple shale and shaly limestone overlie this bed. The rocks just described seldom crop out, commonly weathering back in smooth slopes. In contrast to these rocks the massive light brown sandy limestone about 35 feet above the base of the Three Forks stands out nearly everywhere as a low cliff 15 to 20 feet high. The weathering of this bed is distinctive as its surface becomes smoothly granular or knobby and is crossed by innumerable fine lines at various angles. It underlies about 50 feet of bright red and green fissile shale and thin bedded purple limestone."

In view of the pronounced difference between the Devonian rocks in the thrust sheet and those in the underlying section, it is possible that further studies of the conditions of deposition of rocks of this age may afford a clue to the place from which the thrust mass has been moved and thus may assist in solving some of the puzzling structural problems.

MADISON LIMESTONE

Overlying the Devonian formation with apparent conformity is the Mississippian Madison limestone. This is the uppermost formation in the Sheep Mountain thrust block. Because of its resistance to erosion, it forms the steep cliffs that border the thrust-block plateau. The greatest thickness is about 800 feet, and, as at this place residual pebbles of the next younger, the Amsden, formation are found on the surface of the ground, it is probable that this figure represents approximately the full thickness of the Madison. The formation is bedded, most of the beds being from one to ten feet thick, although some are thinner. Fragmentary fossils are abundant throughout the formation. The limestone is normally cream-colored, but some portions are stained a deep red.

The formations found in the Rattlesnake region between the Madison limestone and the Jurassic Sundance formation do not outcrop in the Sheep Mountain area. These are: Amsden (Mississippian), Tensleep (Pennsylvanian), Embar (Permian), and Chugwater (Triassic). If they ever were present in the upper thrust block, they have been completely removed from it by erosion, and, as yet, erosion has not cut into the lower block deeper than the Sundance formation.

SUNDANCE FORMATION

The Jurassic Sundance is the oldest formation exposed below the thrust plate in the Sheep Mountain area. Only its upper part is exposed, consisting of a massive sandstone and about 150 feet of greenish shales containing *Belemnites* and *Gryphaea*. Outcrops are poor, as the shale slumps considerably.

MORRISON FORMATION

The Morrison formation, lying conformably above the sandstone member of the Sundance, consists entirely of variegated shales with conspicu-

FIGURE 1. NORTH-FACING CLIFFS OF SHEEP MOUNTAIN

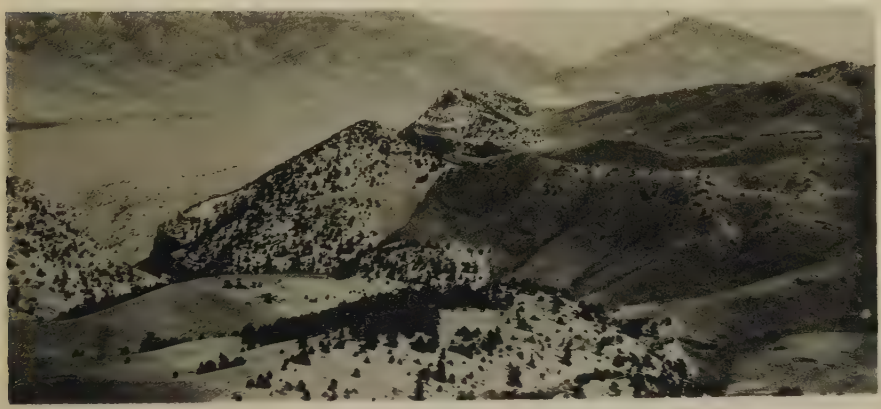


FIGURE 2. TOPOGRAPHY OF THE TOP OF SHEEP MOUNTAIN

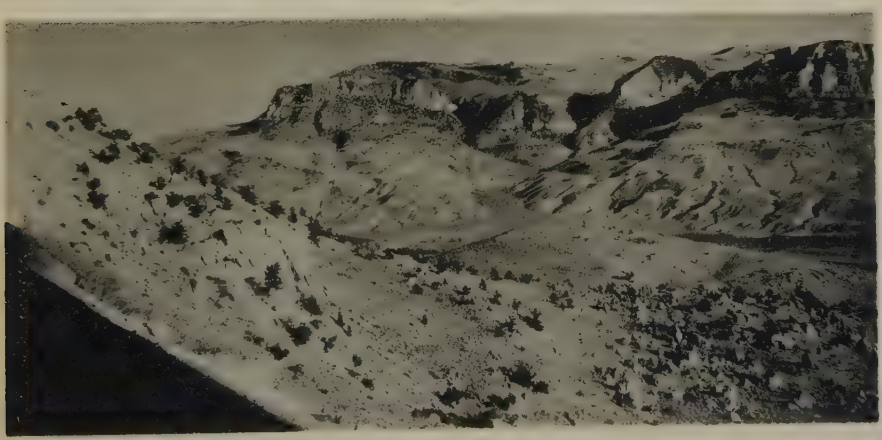


FIGURE 3. CANYONS IN THE NORTH CLIFF OF SHEEP MOUNTAIN

SHEEP MOUNTAIN PLATEAU

FIGURE 1. NORMAL THIN COATING OF THE BRECCIA ON THE LIMESTONE

FIGURE 2. ABNORMAL CONTACT RELATION, WITH THE BRECCIA UNDERLYING THE LIMESTONE

CONTACTS OF THE BRECCIA WITH THE LIMESTONE

ous sandstone lenses. As mapped, this formation probably includes the Fuson shale, for the conglomerate of the Lakota is missing in the area.

CLOVERLY FORMATION

With the Lakota missing and the consequent mapping of the Fuson with the Morrison, the only beds left to map as Cloverly are the upper platy sandstones of the Greybull member. This sandstone is persistent and consequently has been mapped under the term Cloverly.

THERMOPOLIS SHALE

Above the Greybull member of the Cloverly is a black shale which in this area does not show the sandstone members characteristic of the Thermopolis in adjoining areas. The muddy sandstone which is about 20 feet thick in the Rattlesnake section is completely absent in the Sheep Mountain area. Because of slumping in the soft shale of the Thermopolis formation, which in some places reaches the magnitude of mud flows, the thickness of the formation could not be determined. Consequently, in the table, it is combined with the overlying Mowry formation.

MOWRY SHALE

Above the Thermopolis formation is a very hard sandy shale that weathers into blocky fragments. Throughout this formation there are abundant fish-scale impressions along the shaly parting planes.

FRONTIER FORMATION

Above the Mowry shale there is a formation that consists dominantly of sandstone. In good exposures, however, it is seen that there are actually two sandstone members, separated by a thin bed of gray shale. There is also a thin coal seam and a bed of a white clay that may be an altered volcanic ash. The sandstones, because of their massiveness, usually form cliffs on the hillside or, if tilted, form hogbacks.

CODY SHALE

Above the Frontier formation a thick series of gray, poorly bedded shales constitutes the Cody formation. Bedding in this shale is so poor that, except where concretions are found, it is almost impossible to determine the attitude of the formation. Where exposed below the capping thrust plate it has slumped so much that dip measurements are unreliable. The formation is rather fossiliferous at several horizons.

WASATCH FORMATION

Overlying the Cody shale with an angular unconformity that in some places amounts to 10 degrees is the Wasatch formation of red shale and buff sandstone. Near the southern corner of the area, on the flank of the

South Fork "anticline," the Wasatch was deposited across the eroded flank of the anticline and rests on the Frontier sandstone. Throughout most of the region the Wasatch is flat-lying, but locally it is tilted as much as 90 degrees.

VOLCANIC ROCKS

Covering most of the western edge of the area and lapping over on to the plateau formed by the thrust plate is a thick series of volcanic rocks. The age of these rocks has not been definitely determined. On the basis of stratigraphic evidence it appears that they were extruded after a short period of intense erosion, the valleys of this erosion stage being cut into a surface of low relief that truncates both the Heart Mountain thrust sheet and many of the formations on which it rests. The youngest formation underlying the thrust sheet is the Wasatch of the Bighorn Basin. Beds of this formation that underlie the thrust fragments on the McCullock Peaks have been correlated with the Bridger formation (Hewett, 1920, p. 553). Thus, the volcanic rocks must be younger than Bridger, but how much younger must be stated in terms of erosion cycles and thrust faults which cannot be dated accurately. The volcanics consist of breccias and flows, the flows normally basaltic. Certain features of the breccias in the Sheep Mountain area have not been described from other areas, and, as they indicate to some extent the character of the breccia at the time of extrusion, space will be taken for a brief description. For a more detailed description of the volcanics of the Absaroka region the reader is referred to papers by Iddings (1899) and Rouse (1935 and 1937).

In a consideration of the structure of the Trout Creek area, Sheets (1935) notes four kinds of breccias, differentiated on the basis of the mode of deposition. These are: (1) A water-deposited agglomerate; (2) a mud-flow breccia; (3) dry ash and bomb accumulations; (4) an originally semi-liquid flow breccia. All these types of breccia are illustrated in the Sheep Mountain area, although there is very little that could be classed as the ash and bomb accumulation.

Plate 3, figure 1, illustrates what seems to be the normal contact relation between the flow breccia and the limestone of the thrust block. The surface of the limestone is covered with a thin coating of volcanic material but little, if any, change was observed in the limestone itself. Striations visible in the surface smear were probably made by solid inclusions in the breccia. Plate 3, figure 2, shows an abnormal contact relation. The upper rock is the Madison limestone; the lower is the breccia. At the contact the limestone has been slightly recrystallized and has been permeated for several inches by a hematite stain. At the contact the entire rock is stained, but beyond half an inch the stain penetrates only

as minute veinlets. In the breccia there is a zone, about a quarter of an inch wide, in which there are few fragments and where the rock is harder than the rest of the breccia. This seems to represent a chilled phase of the fluid portion of the breccia. It is found only where the breccia directly underlies the limestone. The writer suggests that the breccia flowed under a projecting ledge of the limestone and, due to greater confinement of the heat present in the breccia, the metamorphic effects were greater than in places where the heat was more free to escape. Another possibility, although in the writer's opinion not very probable, is that one of the vents for the extrusion of the breccia rose to the base of the limestone and then spread laterally until it could break through to the surface. Under these conditions an exceptional contact effect would be expected both in the limestone and in the breccia.

At one place, an inclusion in the breccia has been deformed by the flow of the molten rock. The bending of the inclusion indicates a rather high viscosity of the lava, and the formation of small garnets in the inclusion indicates that there was some thermal metamorphism. It is probable that the inclusion is of the Wasatch sandstone, because at another place where the Wasatch is overlain by the breccia there is a similar contact phase, with the formation of small garnets.

At another place there is a rolling surface in the breccia which seems to be the result of turbulent flow between two highly viscous layers in the moving mass. Most of the fragments on this surface have "tails" that may be the result of being dragged by the viscous matrix.

In view of the recent work by Perret (1935) on the characteristics of the *nuée ardente* of Mt. Pelee in particular with regard to the erosive effects of these ash floods on the underlying rock, it will be well to consider whether these could have been important in the deposition of the breccia. Many of the phenomena noted at the contact between the breccia and the limestone might well be explained by these "burning clouds." In Plate 3, figure 1, the striations on the limestone are very similar to those figured by Perret on the rocks underlying the *nuée ardente,* and in the same plate (fig. 2) the zone of hard volcanic rock in contact with the limestone might well be a fused ash. In opposition to the suggestion of the *nuée ardente* is the fact that all known examples of these phenomena are in magmas of an acid nature while the breccias are basic. Another objection is that in many parts of the breccia the fragments are of such diverse nature that they could not have come from the same magma, as is required by Perret's explanation of the formation of the *nuée ardente.* The detail work necessary to confirm or deny this suggestion is beyond the scope of this paper.

From the evidence presented it may be said with fair certainty that

at least a considerable portion of the breccia was extruded as a very viscous flow and that it carried solid inclusions. It is probable, in view of the slight metamorphic changes at the contact with the limestone, that the temperature of the lava was rather low.

STRUCTURE

GENERAL RELATIONS

The area mapped is in a region characterized by asymmetrical anticlines and by thrust faults of relatively small displacement. The larger masses, the Bighorn and the Beartooth Mountains, are almost everywhere bounded on one side by a monocline that may, or may not, show faulting and on the other side by a thrust fault. Smaller mountain masses, such as the Pryor Mountains and Rattlesnake Mountain, are bounded on one side by a nearly vertical fault over which the sediments are draped, and on the other side descend into the Bighorn Basin with a gentle dip slope. On the steep side of the Pryor uplift there is the beginning of thrust faulting (Bucher, Chamberlin, and Thom, 1933, p. 683), and on the steep side of the Rattlesnake Mountain uplift the sediments are slightly overturned (Johnson, 1934, p. 826). Around the margin of the Bighorn Basin are numerous asymmetrical anticlines, most of which, on the west side of the basin, have their gentle side toward the east. It is quite probable that these are features similar in origin to Rattlesnake Mountain but in which deformation has not progressed so far, and in which erosion has not exposed the underlying fault (Bucher, Chamberlin, and Thom, 1933, p. 683).

Thrust faulting in the Bighorn Basin is limited to displacements of only a few miles; therefore, the Heart Mountain thrust, with a minimum displacement of 30 miles and, if the writer's interpretation of its origin is correct, a probable displacement of 50 miles, seems to indicate that the forces involved were of a different character.

The writer's conclusion is the same as that expressed by G. D. Johnson (1934, p. 832)—namely, that the Heart Mountain thrust is the most easterly representative of the great zone of overthrusts that extends from southwestern Wyoming to northern Alberta. If the root of the Heart Mountain thrust is where the writer suggests, it is only 80 miles east of the line of the Darby fault near the Wyoming-Idaho boundary. This spread, occurring as it does at a pronounced bend in the broad zone of overthrust faulting, is too small to exclude the Heart Mountain thrust from this zone.

Remnants of the Heart Mountain thrust sheet lie in an area about 30 miles square, of which the Shoshone Canyon, west of Cody, is approximately the center. This location has been described and figured by Hewett (1920, p. 539). The position of two additional blocks not known

to Hewett has been described by Johnson (1934, p. 832). Field exploration by the writer has disclosed other small limestone blocks which the writer believes to be thrust remnants, although their small size does not definitely preclude the possibility of transportation by some agency other than thrusting. The significance of these fragments will be discussed later.

The greatest known thickness of the rocks in the thrust mass is in Sheep Mountain where the three formations, the Bighorn, the Three Forks, and the Madison, have a combined thickness of 1400 feet. At the highest point on Sheep Mountain, and for some distance down the north slope from it, there is a thin wash of residual pebbles of red mottled limestone, white quartzite, and banded jasper. Probably these were eroded from the Amsden formation, which normally overlies the Madison, although at present there is no Amsden in place in the thrust block. It was not possible to determine whether this postulated erosion took place before or after the block was placed in its present position.

Similar pebbles are found associated with the thrust mass on the McCullock Peaks. Here the fragments of the Amsden are as much as a foot in diameter, and some of the quartzite boulders seem more like the quartzites of the next younger, Tensleep, formation. These two exposures afford the only evidence that formations other than the three exposed in Sheep Mountain may have been involved in the thrusting, and, because the date of the erosion that developed the pebbles could not be determined, the evidence is not conclusive.

STRUCTURE OF SHEEP MOUNTAIN

The fragment of the thrust sheet that forms Sheep Mountain is a relatively undistorted plate of the three formations already noted. At no place is the base visible, but as there are 400 feet of the Bighorn formation exposed in the cliffs above the talus, and as outcrops of the underlying Cretaceous formations occur only a short distance below the top of the talus, it is evident that the plane of thrusting is about at the base of the Bighorn formation. In the northern part of the thrust block the sediments are essentially horizontal, but in the southeastern portion the thrust strata dip northeast at an angle of about 14 degrees. The dip of the strata is presumably parallel to the fault plane, and the attitude of both is apparently the result of a post-thrust movement of which there is evidence in the South Fork "anticline". Evidence will be presented later to show that this "anticline" was not the product of a single orogenic movement, but that the forces making it were active at widely separated intervals of geologic time.

Although, as a whole, the thrust block on Sheep Mountain is rather simple in structure, it includes a few minor structures that merit descrip-

tion. These may be classified as low-angle faults, high-angle faults, folds, and shear fractures. In the main block there is only one low-angle fault. This is on the east-bordering cliff and is entirely within the Madison formation; consequently, its displacement could not be determined. The dip of the fault plane at a place where measurement was possible is N 55° W at an angle of about 43 degrees. In general, the dip is somewhat less, but, because the fault outcrops on the face of a cliff, it could not be measured in a more representative place. A sight reading taken from a point considerably below the outcrop of the fault gave a dip angle of 37 degrees. Good striations parallel to the dip of the fault plane are visible at all places where the plane is accessible. The fault plane itself and all open crevices below it, for a distance of several feet, are filled with a gray clay that contains numerous pebbles of the red mottled limestone, the white quartzite, and the banded jasper characteristic of the Amsden formation. As no pebbles are fractured, it is reasonably certain that they were introduced into the open spaces along the fault plane after all movement on the slip had ceased. The dip of the fault plane, and also the direction of the striations on it, do not correspond with the direction which the writer postulates for the movement of the main thrust mass. They are, however, normal to the axis of the South Fork "anticline". The writer interprets this minor fault as a plane of adjustment within the main thrust block during a post-thrust movement on the South Fork structure. If this interpretation of the fault is correct, it indicates that the Amsden formation was present in the thrust mass, as the large proportion of Amsden pebbles indicates local origin, and the absence of crushing and the lack of striations on the pebbles show that they were placed there after the thrust mass reached its present position. Because the trace of the fault is short and because there is no mappable stratigraphic offset, this fault is not shown on the geologic map.

Another set of low-angle faults is found in one of the discordant blocks in Bear Creek, just west of the southern corner of Sheep Mountain. The direction of movement on this fault cannot be determined, as the direction of the dip of the fault plane and of the striations parallel to this dip does not correspond to the offset of the Devonian formation caused by the fault. There has apparently been a tilting of the entire block after it was sliced, and later settling down the resulting dip of the fault plane has developed striations that have completely obliterated any previous ones. Fractured quartzite pebbles are abundant in the talus below the block, but no evidence was found to indicate that they came from the fault under discussion. It is much more probable that they came from the major thrust plane, which lies a short distance below the top of the talus.

In the Sheep Mountain thrust block high-angle faults are not common, and they do not seem to have any significant bearing on the problems of the thrust. Their abundance in another thrust remnant, across the North Fork, however, makes it advisable to give a brief description of those in Sheep Mountain. One group of these faults is found at the northeast corner of Sheep Mountain, at the junction of the flat-lying beds of the northern portion of the block and the tilted beds of the southeastern portion. There are four faults in this group, their presence indicated by the offset of the Devonian formation on the opposite sides of gullies which follow the fault planes. These gullies are only slightly less steep than the almost-vertical cliffs bordering the thrust remnant; therefore, the fault planes that they follow must have high angles. At no place on any of these four faults, however, was an actual measurement of the angle of the fault possible. The writer believes that these faults were caused by the adjustment of the rather rigid fault block to the post-thrust movement observed in the South Fork "anticline".

Two other faults are found on the north side of the thrust block. One is at the easternmost of the canyons that drain the plateau. The east side has dropped about 20 feet. The other, a little to the west, has a throw of about 25 feet, the eastern side likewise being downdropped.

With the exception of the tilting of the thrust mass adjacent to the South Fork structure, folding in the thrust block is entirely confined to the western edge of the limestone mass. Looking toward Sheep Mountain from the South Fork side the limestone of the thrust mass appears to be flat-lying because the view is normal to the strike. Actually, the dip is about 14 degrees away from the observer. At the left side, viewed from this position, the strata seem to be bent rather sharply downward. The dip at this place is about west-southwest at an angle of about 24 degrees. It was not possible to determine definitely whether the thrust plane was bent with the strata or whether it cuts across the fold. The impression gained, both from a distance and from close up, is that the fault plane cuts across the fold, but the only direct evidence is an outcrop of the Wasatch so close beneath the Madison that there is not room for the Three Forks and the Beirhorn between them. The field relations are such, however, that it is possible that the Wasatch was squeezed up into a wide crack in the thrust block. Though the evidence is not conclusive, the writer believes that the fault plane cuts across the fold.

On the North Fork side of Sheep Mountain the beds are actually horizontal except at the western end. Here, again, the strata make an abrupt bend downward, dipping in some places as much as 10 degrees to the southwest. This downward bend at the western edge of the North Fork cliff is directly in line with that at the western edge of the cliff on the

South Fork side, although the bending cannot be traced from one place to the other because of an intervening cover of the Tertiary volcanics. Again it is impossible to determine with certainty whether the fault cuts across the fold, but here also the weight of evidence seems to indicate that it does.

The origin of the folding at the western edge of the Sheep Mountain block is not known. The folding does not extend into the sediments below the thrust, so it must have been formed before or during the thrust movement. Its northwest-southeast strike is uniform except where it has been affected by the later folding of the South Fork structure. As this strike is that of the larger regional structures, it seems to indicate that, if it were formed prior to thrusting, the Sheep Mountain block was moved from its original position to its present position, without any rotational movement. If the fold was formed during the thrust movement, it would indicate a movement of the thrust mass to the northeast or to the southwest. As will be shown later, movement to the southwest is not possible, in view of the geology of the surrounding areas.

In the cliff of Madison limestone on both the North Fork and the South Fork sides, one very thick bed shows a fracture system that may have considerable bearing on the direction of movement of the fault. Throughout the cliffs, this bed is fractured with a set of joints dipping about 50 to 60 degrees to the northeast. There is no evidence of movement on these joints and no interruption of the continuity of the bed as viewed from a distance. The position of the fractures would indicate that there had been a tendency for the upper beds to move to the northeast with respect to the lower beds, setting up a shearing stress in the thick bed that was relieved by these joints. If this interpretation of the origin of the fractures is correct, it would indicate that the thrust block itself moved to the northeast.

DISCORDANT BLOCKS

At the western edge of the Sheep Mountain thrust mass, and in most places embedded in the volcanic materials, there are many isolated blocks of the Heart Mountain thrust sheet. Most of the blocks seem to lie, if not directly upon the Wasatch, at least not far from the contact between the Wasatch and the breccia. Some of the blocks are certainly resting directly upon the Wasatch, and others just as surely are within the breccia a short distance above the contact. In most exposures, however, the breccia hides the base of the block, so that its relations to the Wasatch cannot be observed.

Plate 4, figure 1, illustrates the appearance of some of the blocks in Post Creek, west of the northwest corner of Sheep Mountain. One of the most noteworthy features of the blocks is apparent; namely, that there

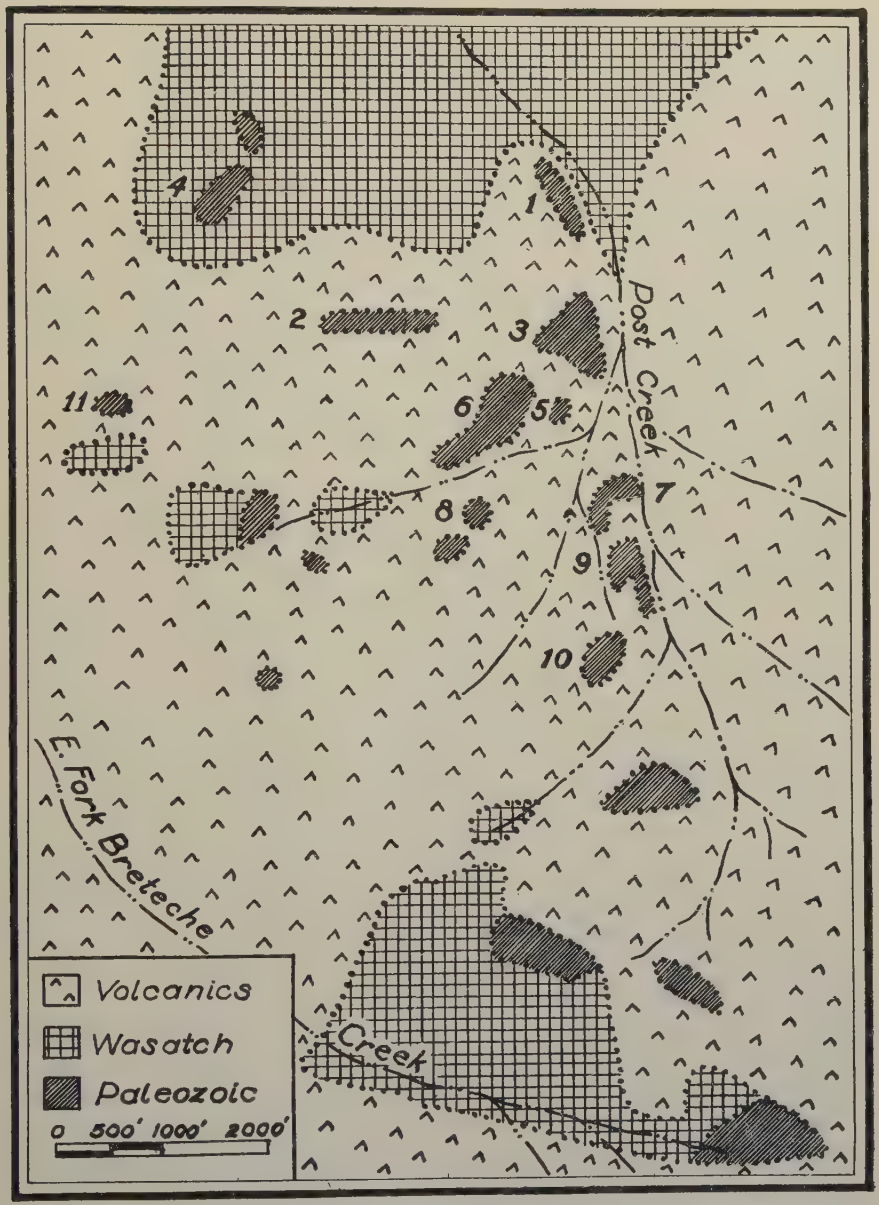


FIGURE 3.—*Sketch map of the discordant blocks in Post Creek*

Numbers refer to individual blocks listed in Table 1.

is no relation between the attitude of one block and that of its neighbor. It is not at all uncommon to find one vertical block and, a short distance away along the direction of its strike, to find another, also having vertical

bedding but with its strike in a totally different direction, in some places at right angles to that of the first one. Also, there seems to be no relation between the attitude of any of the isolated blocks and that of the adjacent Sheep Mountain thrust mass. Southwest of the upper part of Bear Creek there are two large masses of the limestone that are folded in a manner suggestive of the fold along the western edge of the major block, but if they are part of the same fold, their present position, out of the line of the fold, is entirely unexplained. The position of these large blocks aroused speculation regarding the possibility of transportation of overthrust blocks as completely disconnected units rather than as a continuous sheet. Figure 3 is a sketch map of the positions of the discordant blocks on Post Creek. Table 2 gives in detail the dips on certain of these blocks.

TABLE 2.—*Dip readings on several of the Post Creek discordant blocks*

BLOCK NO.	STRIKE	DIP
1	N 25° W	52° E
	N 80° E	60° N
2	N 10° W	18° W
3	N 40° W	24° E
	N 35° W	51° E
4	Mass of fragmental material	
5	E–W	50° S
6	N 10° W	57° W
	N 40° E	70° E
	N 65° E	52° N
	N 15° W	60° W
7	N–S	5° E
	N 45° E	40° SE
	N 20° W	36° W
8	N 30° E	65° W
9	N 15° W	70° W
10	N 80° W	20° N
	N 80° W	29° S
11	E–W	Vertical

As indicated by the difference in the strike of different parts of the same block, many of the outcrops mapped as blocks are really aggregations of variously oriented fragments of considerably smaller size.

Any theory explaining the position of these discordant blocks must be highly speculative, as the breccia masks whatever relation there may be between the attitude of the blocks and the structure of the underlying Wasatch. Several significant facts, however, were noted. A limestone block is usually found with an outcrop of Wasatch in the immediate vicinity, and, in general, the limestone blocks seem to be associated with the higher portions of the pre-breccia topography, as it was developed in the Wasatch formation. Also, where the Wasatch is exposed at the elevation of the base of the blocks, it is, as a rule, highly distorted; whereas at a much lower elevation along the larger stream valleys the beds are either flat-lying or are only slightly contorted. This indicates that the

forces which distorted the top of the Wasatch were surficial, and, as these were probably the ones which moved the limestone blocks, that they were multi-directional. Because of this diversity of direction of application of the deforming forces the drag on the fault plane cannot be considered as a likely explanation.

In an analysis of similar blocks to the west of the Logan Mountain thrust sheet, across the North Fork, Sheets (1935, p. 150) has reached the same conclusion—that the force, or forces, which caused the random orientation of the blocks must have been multi-directional. He has suggested that the blocks acquired their present position as a result of forces connected with the extrusion of the breccia. That such forces affected the tilting of the blocks seems certain, but that they could break up a relatively massive thrust sheet seems less likely. It seems more likely that at the time the breccias were extruded the western edge of the thrust sheet, which is the present line of the discordant blocks, was an area of steep hills of Wasatch formation capped by remnants of the limestone thrust mass. This hypothesis is in harmony with the relation noted between the limestone blocks and the high outcrops of the Wasatch. In adjacent areas there is evidence of a short period of vigorous erosion just preceding the extrusion of the breccia, because, where the breccia overlies the soft Wasatch formation, there are commonly steep valleys in the Wasatch, as much as 800 feet deep, that are filled with the breccia; whereas, in places where the breccia overlies a thrust block, there are no canyons. The evidence seems to point to limestone-capped hills. Also, limestone blocks, slumped down the sides of these hills, would further add to the confusion of dips when the region was later covered by the breccia.

Certain relations on the east side of the valley of Breteche Creek, west of the Sheep Mountain thrust mass, indicate that the breccia flow affected movement of the limestone blocks. Here, a block of the Madison limestone, having almost vertical bedding and an east-west strike, is entirely surrounded by the breccia. On all sides except the south, the limestone has the thin coating of breccia commonly found at the contact between the two rocks. On the south side, however, there is a zone, about 2 feet wide and parallel to the bedding, in which the limestone is intensely sheared, obviously by tectonic forces. The shear zone does not extend into the breccia. About 100 yards south of this block, erosion has cut through the breccias, exposing the Wasatch sandstone. The strata here are vertical, with the top of the beds facing north, and the sandstone more indurated than is common in the Wasatch formation. About half a mile to the west, and at a much lower elevation, the Wasatch is only slightly folded. The writer's hypothesis is that, before the extrusion of the breccia, this block of Madison limestone rested as a capping on a

hill of Wasatch sandstone, the contact being the sheared zone that would be expected at the horizon of the thrust plane. This hill was buried by a breccia flow moving from the south. Because of the high viscosity of the breccia, the top of the hill was tipped over to the north and the limestone capping was carried a short distance beyond its former resting-place.

That large blocks of limestone were picked up by the breccia and were moved for considerable distances is well shown in Carter Mountain, south of the South Fork, where blocks of limestone, at least 50 feet square, are found in the breccia at considerable distances above its base. It seems probable that these blocks were picked up from the ground surface over which the lava was moving, as the contact between the limestone and the breccia shows only the thin coating characteristic of such contacts. If the limestone represents xenoliths detached from the Paleozoic country rock in the rise of the breccia through it, it is probable that they would show a greater contact alteration.

STRUCTURE BENEATH THE THRUST PLANE

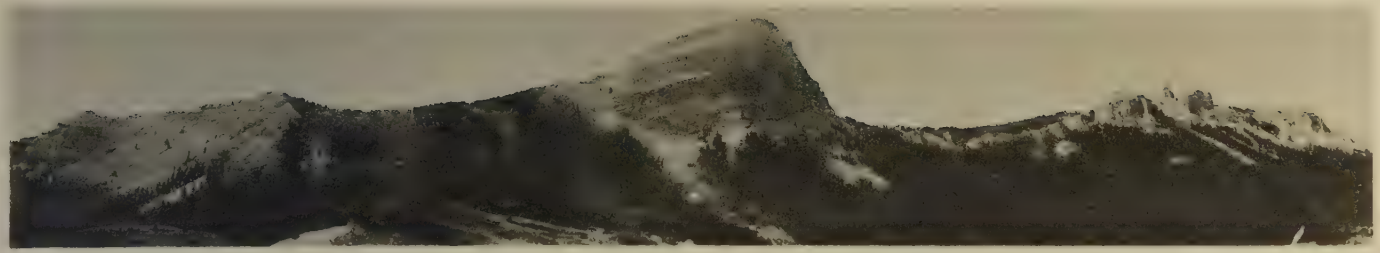
South Fork Valley.—The South Fork Valley has been referred to several times in this paper as anticlinal in structure. In general, this is true, as the sediments on the northwest side of the valley dip rather steeply to the northwest and those on the southeast side of the valley dip at a somewhat gentler angle to the southeast. That it is not a simple anticline, however, is seen from the fact that the Cody shale outcrops high on both valley walls, the succession of beds outcropping beneath it being the normal stratigraphic sequence down to, and including, the Sundance. A fault on each side of the valley results in the Cody shale outcropping on the valley floor. The relations between the Sundance and the Cody formations were first described by Dake (1918, p. 51) as the result of a thrust fault through which the South Fork River had cut. He believed that the fault observed on each side of the valley was a part of one, and the same, fault. Later, Hewett (1920, p. 553) noted that the relations between the formations, at least on the Sheep Mountain side, could be as well explained by the assumption of a normal fault as by a thrust. No evidence was found by the writer that would strengthen or weaken either of these two theories. The beds along the fault in the Sheep Mountain area have slumped so much that it is doubtful if any method, other than geophysical, can determine whether the fault is a thrust fault or a normal one. The most critical area—that where the trace of the fault, extended, would intersect the Cedar Mountain structure—is now buried beneath the waters of the Shoshone reservoir.

Throughout most of the southeast side of Sheep Mountain, along the

FIGURE 1. DISPLACED LIMESTONE BLOCKS IN THE BRECCIA OF POST CREEK

FIGURE 2. FOLD IN THE SEDIMENTS BELOW THE THRUST PLATE AT THE SOUTHWEST CORNER OF SHEEP MOUNTAIN

STRUCTURES AT THE WEST EDGE OF SHEEP MOUNTAIN



Tw Wasatch (Eocene)

Dj Jefferson (Devonian)

Cm Madison (Mississippian)

Obh Bighorn (Ordovician)

Base of Paleozoic exposures

Fault

Sheared pebbles

EAST-WEST SECTION THROUGH HEART MOUNTAIN

PHOTOGRAPH AND STRUCTURE SECTION OF HEART MOUNTAIN

valley of the South Fork, the sediments have a uniform northwestwardly dip. At the extreme southern corner of the area, however, there is an abrupt flexure in which the strike changes about 90 degrees and the dip of the beds becomes vertical. Plate 4, figure 2, illustrates these relations. At the right side of the photograph, two sandstone beds in the Frontier formation, with a bed of white clay between them, dip away from the observer at an angle of about 22 degrees. In the center of the photograph the white bed is again seen, but with a dip of more than 80 degrees to the left and a strike almost directly toward the observer. The Thermopolis and the Mowry formations, which outcrop in normal position below the Frontier formations, are apparently either greatly thinned or perhaps cut out completely where the dip of the Frontier steepens. Extreme slumping in the critical area makes it impossible to determine whether or not these formations are completely missing, but the area occupied by the slump is not large enough to accommodate both formations without thinning.

The writer suggests that this fold is similar to that in Rattlesnake Mountain, and that underlying it there is a fault trending northwest-southeast, along which the southwest side was downdropped. The formations shown in the photograph (Pl. 4, fig. 2) are draped over this fault, much of the thinning occurring in the soft shale of the Thermopolis formation. It is significant that this hypothetical fault would parallel the known fault in Rattlesnake Mountain. The upper beds in the photograph are a part of the thrust sheet and are not involved in the structure to an extent that can be recognized in the field. There is a change in attitude of the formations of the thrust sheet at the place where it crosses the underlying fold, but this change could not be accurately correlated with the fold. The apparent relationship may be purely coincidental.

A short distance southwest of the postulated cross fault, and immediately north of an isolated mound of the breccia known as Castle Rock, is a vertical outcrop of the Wasatch formation with an east-west strike. As this outcrop is followed northward, at right angles to the strike, the formation dips, at first steeply to the north but gradually becomes less and less steep until, within a few hundred yards, it coincides with the almost flat regional dip. This structure is completely isolated and does not seem to be in any way connected with other structures in the area. It is possible that Castle Rock occupies the position of a breccia intrusion that distorted the Wasatch during its emplacement. No evidence was found, however, to confirm this.

The evidence bearing on the tectonic age of the South Fork structure is much clearer than that indicating its character. Johnson (1934, p. 832) has noted that there was a pre-Wasatch uplift of the Rattlesnake Moun-

tain structure. This was also true of the South Fork anticline. West of Bear Creek the Wasatch formation, dipping 10 degrees to the northwest, overlies the Cody shale and, locally, the Frontier. These formations dip in the same direction but at an angle of 22 degrees. Overlying the Wasatch and the Frontier formations, but at an angle of about 6 degrees, is the thrust block of the Paleozoic limestones. This angular relation indicates a rather pronounced arching of the South Fork anticline at some time after the deposition of the Cody formation but before the deposition of the Wasatch. During the erosion that followed this uplift the Frontier formation was exposed on the flank of the arch. This eroded arch was covered by the Wasatch formation which was later tilted by crustal movements that occurred after its deposition but before the time of the Heart Mountain thrust. After this uplift, erosion again exposed the Frontier formation on the flanks of the arch, for at a few points the thrust blocks rest on that formation.

In the previous discussion of the structures of the thrust block it was noted that the limestone of the thrust, adjacent to the South Fork anticline, was tilted from 6 to 14 degrees away from the valley, indicating a post-thrust uplift of the South Fork structure. One later movement of the structure is indicated by the present position of the South Fork Valley along the axis of the arch. In order to have the post-breccia erosion of the region develop a major valley along the axis of a pre-breccia anticline it would be necessary to have a slight arching after the extrusion of the breccia, so that the underlying soft rocks would be brought to a level above the adjacent hard rocks. Under these conditions, erosion, cutting into the soft rocks at the crest of the arch, would tend to follow the axis of the arch. Corroborative evidence was found by J. T. Rouse (1934, p. 740), who observed that the regional dips in the basalt flows above the breccia were from three to five degrees away from the South Fork Valley. Thus, folding of the South Fork anticline has been intermittently active from near the end of the Cretaceous until after the extrusion of the volcanics. The writer does not wish to enter the controversy regarding the exact age of the Absaroka volcanics, which, on the basis of paleobotanical evidence, have been dated from Fort Union to late Miocene. The outline history, however, indicates that they cannot be older than the Bighorn Basin Wasatch, which, as previously noted, has been correlated in part with the Bridger formation of upper Eocene age.

North Fork Valley.—Beneath the thrust sheet on the North Fork there is little observable structure. The Cody shale, nearly horizontal or dipping slightly to the west, is overlain with a slight angular unconformity by the Wasatch formation. This overlap occurs only at the western edge

of the thrust mass, so that throughout most of the area the thrust rests on the Cody shale. In most places the structure of the Cody cannot be determined, both because of the poor original bedding and because of the great amount of slump that occurs wherever the formation outcrops on a steep slope. The conclusion that the formation probably dips slightly to the west is based on a few poor exposures in the area mapped and on better ones a little to the west of the area. The relation between the thickness of the formation and the length of the exposures from east to west confirms this conclusion.

In a few exposures at the eastern end of the area the Cody shale is intensely contorted, but, as this condition does not exist farther west, the writer considers that it is either the result of adjustments in the shale during the folding of the South Fork anticline or that it is the kneading of the shale in a slump mass. In the area where the contortions are found there is no present evidence of slumping, but in an earlier stage of the present erosion cycle it is quite probable that some did occur in this place. The position of the contortions at about the zone where the tilted beds of the South Fork anticline flatten out would favor the theory that the folding in the Cody was an adjustment during the formation of the South Fork structure. As these contortions are 1200 feet below the level of the thrust plane, it is improbable that there is any connection between them.

At the northwest corner of Sheep Mountain is an outcrop of an unfossiliferous sandstone. The outcrop is small and the rocks are quite distorted, the beds in general standing at an angle of about 80 degrees. The sandstone, approximately at the level of the thrust plane, rests on the Cody shale. No positive evidence could be found in this outcrop that would determine the age of the rock. It has been mapped, however, as Sundance, on the basis of its lithologic similarity to a portion of a fossiliferous remnant of the Sundance formation, found at about the same elevation and in a similar structural position directly across the North Fork Valley. This undoubted Sundance also rests upon the Cody shale at about the level of the thrust plane, but at least a portion of it is covered by breccia, the thrust sheet having been completely removed by erosion before the extrusion of the breccia. The fossils in this Sundance rock are sheared badly. In particular, the Belemnites are fractured perpendicular to their length, and many of them are recemented, some with as many as four offsets in one individual. The Gryphaea are not so badly broken, apparently being strong enough to resist the shearing forces. Because of the position of this outcrop and the sheared condition of the fossils, the writer believes that the rock was carried to its present position by drag or the plane of the Heart Mountain thrust. The same mechanics are suggested to account for the position of the remnant on Sheep Mountain.

CARTER MOUNTAIN AND MEETEETSEE MOUNTAIN THRUST REMNANTS

In a search for more evidence on the extent of the Heart Mountain thrust, the writer made a brief trip along the east front of Carter, Middle, and Meeteetsee mountains, seeking hitherto unknown limestone thrust remnants. These mountains are south of Cody, Wyoming, and north of the Greybull River. They are erosional mountains, carved from the breccia and basalt flows that characterize the Absaroka region. In the limited time available it was possible to visit only the portion of the mountains adjacent to the very poor roads leading to the sheep camps.

The first place visited was at the head of Hoodoo Creek, on the east side of Carter Mountain. Limestone fragments are rather common in the gravel of Hoodoo Creek. These continue in the gravel upstream from the point where the creek leaves the breccias, but at the contact between the breccia and the Wasatch no limestone was found resting on the Wasatch or in the breccia. Upstream, at a point about 400 feet higher, an outcrop of the Wasatch was found which was apparently the top of a pre-breccia hill now exposed by erosion through the breccia. Here, considerable limestone was found both at the contact between the breccia and the Wasatch and incorporated in the breccia for some distance above the contact. It was impossible to determine at this place whether the limestone was already on the surface at the time of the breccia flow or whether it was carried by the breccias for a considerable distance. Its concentration at the top of a pre-breccia hill, however, seems to preclude the possibility of transportation by the breccia.

The next place visited was at the head of Meeteetsee Creek. Here, limestone was again found at the contact between the breccia and the Wasatch. It was not so apparent that the limestone was associated with the top of a Wasatch hill, but the elevation where the fragments were found was higher than that of many breccia outcrops along the mountain front. Here, again, it was not possible to determine whether the limestone was carried by the breccia or was present on the Wasatch surface at the time of the breccia extrusion.

At the next place visited, however, relations were found that could only be explained by assuming that the limestone fragments were present as residual blocks on top of the hills of Wasatch before the arrival of the breccia. Rawhide Creek has cut deeply into the breccia, without, however, cutting through it into the Wasatch beneath until it emerges from the mountains. In its valley, no limestone blocks were found, and no limestone gravel was found in the creek bed. However, just over the divide between Rawhide and Rose creeks the Wasatch is exposed at an elevation considerably above the level of Rawhide Creek. As there has been no strong post-breccia folding in this region, the only explanation

possible is that this outcrop represents a hill in the pre-breccia topography and that the present valley of Rawhide Creek is located in the position of a deeper pre-breccia valley.

At the contact between the Wasatch and the breccia there are numerous blocks of the Madison limestone, the largest about 7 feet in diameter. The physical relations are as follows. The breccias of the Absaroka region have covered a topography in the Wasatch formation of greater relief than that now developed at this point in the Rawhide Creek drainage. There are no limestone blocks in the breccia, except at a point immediately above the top of one of the pre-breccia hills, and no limestone could be found in the gravels of Rawhide Creek, even at the place where it passed from the breccia to the Wasatch. Thus, it is inferred that at the time of the extrusion of the breccia there was a mantle of limestone boulders on the tops of the Wasatch hills and that the slopes were gentle enough so that little of this limestone moved down the slopes. This condition could only result from the erosion of a rather flat region over which there was a comparatively abundant cover of the limestone. Initially the limestone masses must have been very large, in order to have persisted through this long erosional period and to have retained their present size. Transportation of the limestone by thrust faulting seems to be the only process adequate to account for the cover of large blocks.

The writer believes that the evidence presented is strongly indicative that at one time the Heart Mountain thrust extended over this area, at least as far as the present position of the limestone fragments. This extends the known area of the thrust remnants 10 miles southward.

HEART MOUNTAIN REMNANT

In the summer of 1934, the writer and G. D. Johnson spent two days mapping the Heart Mountain remnant. Although this time was not sufficient to work out the structure in detail the writer received several definite impressions that may be worth recording. Although in agreement on the facts of the structure, Johnson did not entirely agree with some of the writer's interpretations.

A view of the Heart Mountain thrust remnant, from either the north or the south, shows that both the east and the west ends are thin with respect to the middle, which stands up as a "beehive-like" knob (Pl. 5, fig. 1). Plate 5, figure 2, is a structure section, looking south. From this section it is apparent that the Heart Mountain remnant is a flat sheet, cut by a transverse north-south fault just east of the central knob. At the west end of the remnant there are several east-west-trending faults of small displacement, but as these are parallel to the section they do not show on it.

A feature which the writer considers to be of great significance is the character of the Wasatch just east of the transverse fault. Here the clay of the Wasatch is greatly contorted, and kneaded into it are many pebbles and cobbles of limestone and quartzite, many of which have been intensely sheared and some of which have been recemented after shearing. A pebble count showed that the limestones were the most abundant, with white quartzites next. There were relatively few of the dark-colored quartzites that are commonly found on the eroded surfaces of the Wasatch formation. The limestones and the white quartzites were apparently derived from the erosion of the Madison and the Amsden formations, perhaps from the thrust sheet itself; the darker quartzites, although apparently of pre-Cambrian types, were probably derived from erosion of the Wasatch.

The writer's interpretation of the structure of the Heart Mountain remnant is that during the early stages of the thrusting it was a flat sheet and included all of the Madison formation and probably the Amsden in addition to the Bighorn and the Jefferson. Other formations younger than the Amsden may have been present, but there is no evidence now concerning them. During the thrusting the thrust plate was subjected to erosion, and fragments of it were deposited as gravel in front of the advancing edge. This gravel was later overridden by the thrust sheet. At some time during the thrusting the transverse fault developed, and the western side, dropped below the eastern, acted like a road scraper, gathering the basal gravel before it and kneading it into the Wasatch shale. The rotational stresses set up by the increased friction would tend to increase the displacement on the fault and cause the bending of the strata to the west. During this process the "road-scraper" edge of the overriding fault block was probably broken and abraded, preventing it from extending far below the fault plane.

More detailed work on this remnant is needed, but, if the interpretation expressed here is correct, it is clear that the Heart Mountain thrust remnant was placed in its present position by forces acting over a long period of time. Although the exact direction of movement could not be determined, the presence of the contorted shale on the east side of the transverse fault indicates that the movement was, in general, from the west.

DIRECTION AND AMOUNT OF MOVEMENT OF THE HEART MOUNTAIN THRUST

The direction of movement of the Heart Mountain thrust has not been satisfactorily determined. Dake (1918) and Hewett (1920) both believed that, because the general structural features of the region to the north, the east, and the south were well known and showed no evidence

of the root of a major thrust fault, the thrust must have come from the west. In this direction the thick cover of the Absaroka volcanics would hide the root of the thrust.

During the summer of 1934, Dake, working on the details of the structure of the upper South Fork Valley, found what he tentatively regarded as a minor low-angle thrust fault, with movement from northwest to southeast, and he suggested that the movement of the Heart Mountain thrust might have been in the same direction. Further field work the following year, in which the writer participated, disclosed that the minor thrust was actually a combination of a high-angle reverse fault and a completely recumbent fold. The upper block of the reverse fault has moved to the northwest with respect to the lower block, and the recumbent fold is overturned to the southeast. The relation of this fold to the regional structures has not been determined, but its existence indicates forces acting at essentially right angles to the prevailing regional forces as deduced from the Bighorn Basin, the Bighorn and Beartooth mountains, and the Rattlesnake anticline.

In spite of the evidence of compressive forces acting in a northwest-southeast direction, it seems impossible that the Heart Mountain thrust could have come from the northwest, because, if a line is drawn northwestward from the Heart Mountain thrust remnant, it enters the pre-Cambrian core of the Beartooth Mountains without having crossed a fault of sufficient magnitude to be the root portion of the Heart Mountain thrust.

The amount of displacement necessary to explain the present position of the thrust remnants is very great, regardless of the direction of movement assumed. In the following estimate of the amount of thrusting necessary to account for the present position of the remnants it is assumed that the fault is one of conventional type—i. e., that it originated along a line and moved in a direction essentially perpendicular to that line. The writer does not consider that radial landslide thrusting, of the type described in the Bearpaw and Highwood mountains, could produce displacements of the magnitude observed in the Heart Mountain thrust. The only possible position for a center of this type is in the region of Trout Peak, which is 40 miles from the McCullock Peak remnant of the thrust sheet.

The minimum displacement that would account for the location of all the remnants of the thrust sheet would be 33 miles and would involve a thrust from northwest to southeast. As already stated, such a direction is not thought possible, as the structure between the Heart Mountain remnant and the pre-Cambrian of the Beartooth Range has been thor-

oughly worked out and no fault that could be the root of the Heart Mountain thrust is present.

If the thrust moved from west to east, a displacement of 40 miles would account for the position of all the known remnants. This direction is a possible one, as the entire area where the root would lie is now covered by volcanics of the Absaroka Range. It is not a probable one, however, as there are no other major structures in the region with a north-south strike.

If the thrust mass moved from southwest to northeast, which would seem the most probable in view of the orientation of the major regional structures, the amount of displacement necessary to place the remnants in their present positions would be about 48 miles. In spite of the greater amount of displacement required by assuming movement in this direction, there is a certain amount of direct evidence favoring it. At the southwest corner of Sheep Mountain an outcrop of Wasatch sandstone was found, at about the level of the thrust plane, and that sandstone is steeply tilted and more indurated than is common in the Wasatch formation. Its strike is N 50° W, and its dip about 80° NE. The determination of the angle of dip is open to question, but the northwesterly strike is clearly evident in the field. The strike of this outcrop, however, is not conclusive evidence of the direction of movement of the thrust, because of the contortions noted in the Wasatch, which have been described as the result of the breccia flows, but, as this outcrop is about at the level of the thrust plane and is not more than 100 feet from the nearest thrust remnant, it may be of more significance.

Another indication that the thrust was from the southwest is found in the attitude of the rocks at the western edge of the Sheep Mountain remnant. As has been stated previously, the nearly horizontal beds of the thrust mass bend down abruptly to the west, along the western edge of the plate. The strike of this fold is approximately northwest-southeast, and it must have developed before the thrust sheet reached its present position, as it does not involve the sediments below the thrust plane. It is probable that this fold was formed during the movement of the thrust mass and thus would indicate a movement to the northeast.

A third indication that the thrust moved from the southwest to the northeast is found in the fractures previously described as present in a thick bed in the Sheep Mountain thrust mass. These fractures, striking northwest-southeast and dipping to the northeast, are very suggestive of tension fractures, caused by the upper beds moving to the northeast with respect to the lower ones.

Another feature of the regional geology that may be related to the Heart Mountain thrust is a belt of Tertiary intrusives, extending through

the center of the Absaroka volcanics in a northwest-southeast line. The writer suggests that these intrusions may mark a line of weakness, determined by the root of the Heart Mountain thrust. If this is true, it would indicate a minimum displacement of 55 miles.

MECHANICS OF MOVEMENT OF THE THRUST

In this analysis of the direction and extent of the thrusting, it has been assumed that all the remnants of the thrust moved to their present position along paths that were approximately parallel. The movement would then have to be either that of a solid plate over the entire area or that of isolated blocks in the same direction. The field relations at the western edge of the Sheep Mountain mass suggest strongly that the several large blocks in the Bear Creek drainage system did not move as a connected mass which was later broken by erosion, but that they were placed in their present positions as individual blocks. They are all apparently parts of the down fold at the western edge of the main block but seem to have been separated from it and rotated so that, in them, the strike of the beds is no longer parallel to that in the main block. These blocks are too large to have been moved by the breccias. The blocks referred to are not the discordant blocks previously discussed but are much larger. They are shown on the map at the southwest corner of the Sheep Mountain thrust block (Pl. 1).

It has been partly because of this peculiar relationship that several mechanisms, which have been suggested for the movement of the Heart Mountain thrust, are radically different from the conventional conception of the mechanics of large overthrusts.

One of these theories, suggested by W. H. Bucher (1933), is that an explosion of volcanic gases, presumably in the region now occupied by the Absaroka Mountains, tore loose a sheet of the Paleozoic limestones and hurled its fragments to their present position, perhaps riding on a cushion of steam. Further work in the region has failed to reveal evidence supporting this theory. Another suggestion, made by W. T. Thom, Jr., at a meeting of the Yellowstone-Beartooth-Bighorn Research Association, was that, so far as the known evidence indicates, the Heart Mountain thrust might be similar to the landslide faulting around the Bearpaw Mountains, described by Reeves.

In a recent paper the writer (Stevens, 1936) has suggested another mechanical principle which might operate to move a continuous sheet or isolated blocks over the surface of the earth. Lawson (1922) has shown that, even under the most favorable conditions, a thrust plate more than about 30 miles in length would not be strong enough to transmit the force necessary to overcome the resistance of friction on the fault plane. In

the Heart Mountain fault the competent rocks of the thrust plate are so thin that any slight flexure should cause shearing in the thrust mass; yet no shearing is found, although the fault has a minimum displacement of 40 miles. The writer suggests mechanics which are essentially those of under-thrusting, except that the forces accumulate at the back of the lower block and are then relieved suddenly, causing a slight movement of the lower block. If this movement was sudden enough, not enough force could be transmitted across the fault plane to move the upper block a distance equal to the distance moved by the lower block. The effective force operating to hold the upper block in place is its inertia. This process can be illustrated experimentally by placing one block of wood upon another and then striking the lower one horizontally with a hammer. The lower one will move, but the inertia of the upper one will hold it in place, causing a displacement between the two blocks. That this represents the mechanics of the Heart Mountain thrust has not been proven, but the writer believes that the field relations are better explained by such mechanics than by any other that has been suggested. It is possible, under such mechanics, that the Heart Mountain thrust mass either comprised a group of isolated blocks moved across the surface of the earth by reason of their inertia, or, more probably, that it was a continuous sheet which became detached from its root at its western edge and moved for some distance, relative to the rocks on which it rested, because of its inertia. Friction on the thrust plane might cause the western edge to fracture and the fragments to become twisted with respect to the main mass.

OUTLINE HISTORY OF THE AREA OF THE HEART MOUNTAIN THRUST

1) Deposition without local earth movements up to and including the Lance, possibly the Fort Union.

2) Arching of the Rattlesnake and South Fork anticlines.

3) Erosion exposing the Paleozoics on Rattlesnake Mountain, possibly as deep as the Madison; and the Frontier formation on the South Fork anticline. This is shown by the strong angular unconformity between the Wasatch and the older formations in these two places.

4) Deposition of the Wasatch, at least 1500 feet. As no Fort Union outcrops in the folded area the relation of this formation to the folding has not been determined.

5) Uplift and erosion west of Cody. This is indicated by the absence of Wasatch between the west end of Sheep Mountain and the town of Cody.

6) Erosion to virtual peneplanation. This is indicated by the manner in which the Heart Mountain thrust cuts across hard and soft formations.

7) Heart Mountain thrust fault.

8) Renewed uplift on the Rattlesnake and South Fork anticlines and also on the small fault west of Sheep Mountain. This was combined with regional uplift that started the erosion of the overthrust mass.

9) Erosion continued essentially to peneplanation. At the end of this erosional period most of the thrust sheet had been eroded away, but because of its protected structural position, between the Rattlesnake and South Fork anticlines, a mass was left that has been since cut up into Sheep Mountain and Logan Mountain. At this time the land surface was unaffected by the resistance of the different formations, the limestone thrust remnants and the Wasatch sandstone lying at the same level.

10) Regional uplift, probably greater on the anticlinal axes, although there is no direct evidence of this.

11) Period of very rapid erosion that cut canyons to a depth of about 1000 feet in the soft Wasatch formation but had little effect on the harder limestones of the thrust masses.

12) Extrusion of the breccia and basalt flows. (A detailed history of this period is given by Rouse, 1934.)

13) Further uplift of the Rattlesnake and South Fork anticlines.

14) Present erosion cycle started, the course of the North Fork determined as a consequence of the slope of the lavas; that of the South Fork by the arch of the lava caused by the uplift of the South Fork anticline noted in 13.

CONCLUSION

From the known exposures, both in the Sheep Mountain area and in those adjacent, it is impossible to prove the direction of movement of any of the thrust masses. The writer has cited the evidence that he believes indicates that the Sheep Mountain block moved from southwest to northeast and has expressed the opinion that the Heart Mountain thrust is the easternmost of the great belt of Rocky Mountain thrust faults. Due to the great extent of this fault in a direction parallel to the movement (whichever way the movement may have been), the factor of the strength of the thrust plate as opposed to the friction on the thrust plane would be of great importance, and the writer believes that the inertia mechanics suggested for low-angle faults in general would be applicable to the Heart Mountain thrust. This theory permits the relative movement of large detached surface blocks over the underlying material and could account for the peculiar rotated blocks west of Bear Creek. Whether the several remnants of the Heart Mountain thrust moved as isolated blocks or as a connected plate could not be determined, as erosion following the period of thrusting has all but removed the thrust material.

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